The Nature of V838 Mon and Its Light Echo
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Hubble Space Telescope Observations of the Light Echo around V838 Monocerotis

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Abstract. The outburst of V838 Monocerotis in early 2002, and the subsequent appearance of its light echoes, occurred just before the installation of the Advanced Camera for Surveys into the *Hubble Space Telescope* (*HST*). This fortunate sequence of events has allowed us to obtain spectacular *HST* images of the echoes, yielding not only pictures of extraordinary beauty, but also providing unique scientific information.

Our team has used the *HST* images to provide a direct geometrical distance to V838 Mon, based on polarimetric imaging, and limits on the distance based on the apparent angular expansion rates.

Several morphological features seen in the *HST* images strongly suggest that the illuminated dust was ejected from the star in a previous outburst, similar to the current one. In particular, a "double-helix" feature points exactly back to the star. Moreover, three-dimensional mapping of the outer edges of the dust suggests an overall ellipsoidal shape, centered on V838 Mon itself. And the appearance of the light echo in the most recent *Hubble* images is remarkably similar to that of a well-known planetary nebula, M27.

Future work on the *HST* images will include an analysis of interstellar-dust physics, in a situation where the scattering angle and illumination are unambiguously known, and visualization of a fully three-dimensional map of the dust distribution.

1. The Hubble Space Telescope

The *Hubble Space Telescope* (*HST*) has recently celebrated its 16th anniversary in orbit, having been launched aboard the NASA space shuttle in April 1990. Since then there have been four astronaut servicing missions between 1993 and 2002 (SM 1, 2, 3a, and 3b). We are currently hoping that there will be an SM4 in 2008, during which two new instruments would be installed: the Cosmic Origins Spectrograph (COS) and the Wide Field Camera 3 (WFC3). WFC3 will be a remarkable instrument that provides direct imaging at UV, optical, and near-IR wavelengths.

The *HST* is uniquely suited for high-resolution imaging. In this paper I would like to present some results from *HST* imaging of the remarkable light echoes around V838 Monocerotis.

2. HST Observations of V838 Mon

Shortly after V838 Mon reached maximum light in February 2002, an expanding light echo was discovered by Henden, Munari, & Schwartz (2002). These light echoes have evolved to become the most spectacular display of the phenomenon in astronomical history. They have been the subject of extensive imaging by ground-based observers (e.g., Crause et al. 2005 and references therein), and are of course the inspiration for the conference here in La Palma.

Based on the highly structured appearance of the initial ground-based images, our team proposed for Director's Discretionary (DD) time on *HST* for a program of direct imaging and imaging polarimetry. The team members are as follows: S. Starrfield (Arizona State University); Z. Levay, N. Panagia, W. Sparks, B. Sugerman, R. White, and myself (STScI); A. Henden (AAVSO); M. Wagner (University of Arizona); R. Corradi (Issac Newton Group); U. Munari (Padova University); L. Crause (SAAO); and M. Dopita (ANU).

We received *HST* observing time at five epochs in 2002 through DD allocations: April, May, September, October, and December. All of the observations were made with the Advanced Camera for Surveys (ACS), which had been installed in *HST* during SM3b in March 2002. I need not emphasize to this audience how extraordinarily unfortunate it is that no *HST* observations were obtained during 2003—the loss of this opportunity is truly incalculable. However, the echoes were imaged twice in 2004 through the Hubble Heritage program, in February and October. More happily, the *HST* Cycle 14 allocation committee did award our team observing time for an intensive *HST* imaging campaign from October 2005 to January 2006, and we also have two more epochs of observations scheduled in Cycle 15 for late 2006 and early 2007.

A summary of results from the 2002 imaging is given by Bond et al. (2003). A discussion of the imaging polarimetry is presented elsewhere in these conference proceedings (Sparks et al. 2006).

It is nearly impossible to represent the extraordinary *HST* images on paper, especially in black and white. As a partial guide to what is available, Figure 1 presents a montage of the *HST* images from 2002 and 2004, all at the same angular scale. However, I urge readers to go to the STScI website (www.stsci.edu), and of course to the Hubble Heritage site (heritage.stsci.edu), where many full-color images of the light echoes can be viewed.

An animation showing all of the *HST* images has been prepared by Zolt Levay and myself. There is a link to this animation at the conference website, www.ing.iac.es/conferences/v838mon, or you can view it at www.stsci.edu/~bond/v838mon_2002-5_anim.gif.

3. Applications of the HST Images

In addition to their aesthetic beauty, the *HST* images of the V838 Mon light echoes provide several scientific applications. These include direct geometrical distance determinations, and information on the detailed morphology and three-dimensional structure of the circumstellar dust. (The images will also ultimately provide important information on the physics of interstellar dust particles, since

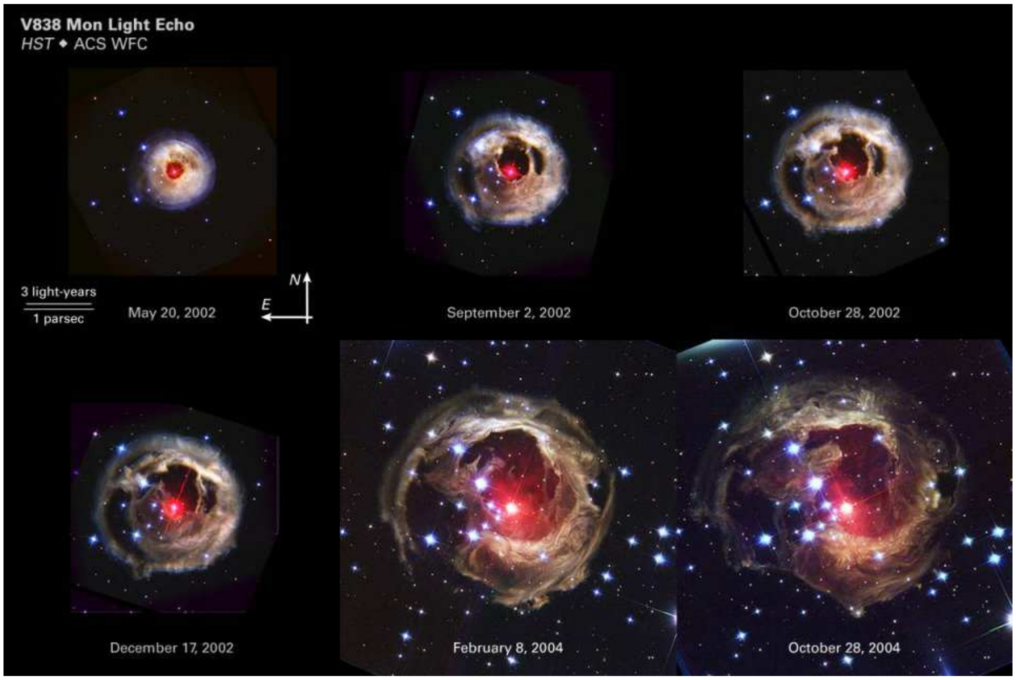

Figure 1. *HST* images of V838 Mon, 2002-2004. The images are all at the same angular scale, and dramatically illustrate the apparent expansion of the echoes. Images taken in late 2005 and early 2006, however, have nearly the same size as the October 2004 image, indicating that we are about to enter the phase of apparent contraction.

we are in an unique situation where both the spectrum and time dependence of the illumination, and the scattering angle, are unambiguously known.)

3.1. Geometrical Distance Determinations

Light echoes provide two independent means for geometrical distance determinations. One method is based on apparent angular expansion rates, and is described in detail by Bond et al. (2003). This method requires an assumption about the geometry of the dust. For the 2003 analysis, we assumed thin, spherical sheets centered on the star, and were able to obtain a lower limit to the distance of $\sim$2 kpc.

We will carry out a similar detailed analysis of the *HST* images from the 2005-6 campaign, but an approximate calculation goes as follows: In late 2005, the radius at which zero apparent expansion would be seen (for spherical shells centered on the star) would be $\sim$1400 light-days. The corresponding angular radius of zero expansion would be $40'' \times (6\,\mathrm{kpc}/d)$, where d is the distance. The apparent expansion in the late 2005 *HST* images is indeed close to zero at a radius of about $40''$, consistent with an approximate distance of $\sim$6 kpc (see next paragraph). At larger radii, the echoes are clearly still expanding, indicating that the distance cannot be much less than $\sim$6 kpc.

The other geometrical method relies on polarimetry. This method was worked out in detail more than a decade ago by our team member Bill Sparks (Sparks 2004). His intention was to use the technique to find distances to extragalactic supernovae, but the method now finds its application to a peculiar object in our own Milky Way! The Sparks technique is based on the fact that maximum linear polarization occurs for scattering off of dust particles at an angle of 90°. Given the geometry of light echoes (e.g., Bond et al. 2003; Sugerman 2003), this location corresponds to a linear radius of $c\Delta t$, where Δt is the time since the outburst. The corresponding angular radius of maximum linear polarization then yields the distance. As described elsewhere in these proceedings, the *HST* polarimetric images yield a distance of 5.9 kpc (Sparks et al. 2006). Reassuringly, this agrees very well with the distance of 6.2 kpc recently obtained from spectral classification and photometry of three B-type stars in the sparse, young cluster surrounding V838 Mon (Bond & Afşar 2006; Afşar & Bond 2006).

3.2. Morphology of the Light Echoes: Is the Dust Interstellar or Ejected from the Star?

In this subsection, I want to discuss the issue whether the dust illuminated in the light echoes arises from material ejected from V838 Mon in previous outbursts, or is merely ambient dust with no special relation to V838 Mon (as advocated, for example, by Tylenda 2004 and Crause et al. 2005). My approach is not based on physics, but upon the morphological approach described so brilliantly by Zwicky (1957). I conclude that the dust was indeed ejected from V838 Mon. Apart from the fact that the star is copiously producing dust during its current outburst, and that that dust will expand slowly away from the star and would be illuminated by any future outburst, there are the following morphological arguments:

1. *There are features in the dust that show a connection with the star.* The most dramatic one is the "double-helix" structure seen in the *HST* images of September, October, and December 2002 (which was discussed by Carlqvist 2005). The axis of the helix points directly at the star in all three images, one of which is shown in Figure 2. It would be remarkable to find such a precise alignment if the dust were merely ambient interstellar material that happens to lie in the vicinity of V838 Mon.

   Note that the three-dimensional location of any illuminated dust particle is unambiguously known in a light echo. We plan to develop three-dimensional visualizations of the dust distribution, which will doubtless provide further information on the relationships between the dust and the star. At a given epoch, the illuminated dust lies along a paraboloid with the star at its focus.

2. *The dust has a well-defined outer edge, and the distribution of outer edges is centered near the star.* As a simple example of three-dimensional mapping, I marked the outer edges of the dust distribution in each of the available *HST* images. As noted in the previous paragraph, the (x, y) position of any feature in the echoes at a time Δt corresponds exactly to a z location in the line of sight (z does, of course, depend also on the distance to the star, but as noted above d is now well known).

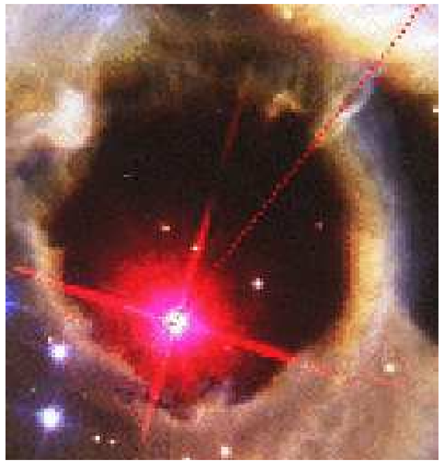

Figure 2. Detail from *HST* image of the V838 Mon light echo on 2002 September 2. A dotted line drawn from V838 Mon through the "double-helix" feature at the upper right passes precisely through the axis of the helix.

The images in 2002 have very sharp outer edges (see Figure 1), indicating a sharp drop in the dust density at the corresponding locations in three-dimensional space (since the edges are much sharper than would be produced by purely geometrical effects). The color images obtained by *HST* are particularly useful, because they contain obvious sharp blue rims, corresponding to the sharp blue peak at maximum in the light curve. The edges are not quite as sharp at later epochs, but are still easily located. Until we can present a fully three-dimensional visualization of the dust, I have simply measured the locations of the outermost edges along a north-south axis passing through the star, and along an east-west axis. I then converted these locations in the plane of the sky to the true three-dimensional locations. The resulting maps of the outer edges are shown in Figure 3a (north-south), and Figure 3b (east-west).

Several authors concluded from the 2002 data that the dust edges defined a plane, and suggested that this implied an interstellar origin for the dust. However, with the inclusion of more recent observations, our Figures 3a and 3b show that there is now clear curvature in the dust fronts. In fact, it appears that the distribution is consistent with a roughly ellipsoidal structure, whose center coincides approximately with the location of V838 Mon. Such a morphology strongly suggests an origin from the star itself, rather than a feature that arose by chance.

3. *Recent images appear to show an "equatorial plane" passing through the star.* Figure 4a shows the *HST* image obtained on 2005 November 17. A dashed line has been added to guide the eye to regions of enhanced surface brightness that lie on both sides of the star.

   This image bears a remarkable similarity to that of a typical planetary nebula, M27 or the "Dumbbell Nebula." An amateur photograph of this

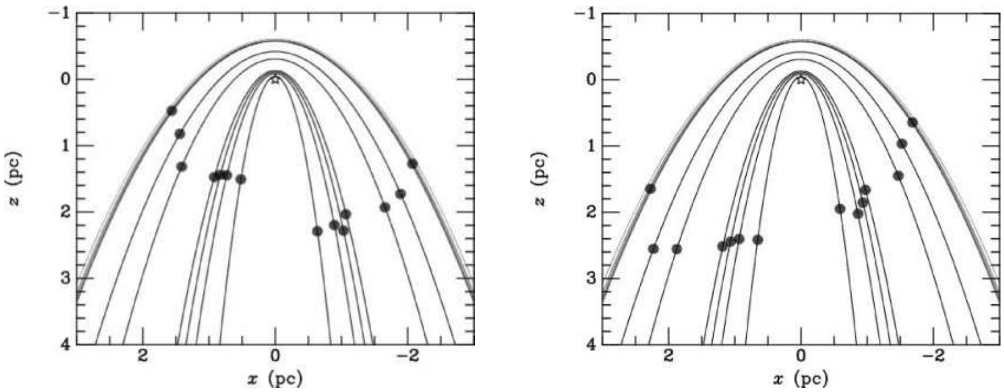

Figure 3. Maps showing the locations of the outermost edges of the light echoes seen in the available *HST* images from 2002 (inner parabolas), 2004 (two intermediate parabolas), and 2005-6 (densely packed outer parabolas). The edges are shown in a north-south plane centered on V838 Mon (left), and in an east-west plane (right). Each parabola corresponds to the location of the illuminated dust at that epoch, and the large black dots show the (x, z) location of the outer edge along the corresponding parabola. Note that the x and z scales are in parsecs, and V838 Mon itself is located at the origin of coordinates. Both maps suggest that the dust lies in an ellipsoidal distribution, centered near the star.

nebula is shown in Figure 4b, which clearly demonstrates an equatorial feature on either side of the central star.

There is no doubt that M27 was ejected from its central star. The striking resemblance of the light echo in late 2005 to a genuine planetary nebula provides another strong morphological argument that the illuminated dust was indeed ejected from the star.

4. Conclusion

V838 Monocerotis is illuminating the most spectacular light echoes seen in the history of astronomy. The high spatial resolution provided by the *Hubble Space Telescope* has yielded images of extraordinary beauty, as well as providing unique scientific information.

The *HST* images have provided a direct geometrical distance to V838 Mon, based on polarimetric imaging. Angular expansion rates have also given limits to the distance.

Several morphological features seen in the *HST* images strongly suggest that the illuminated dust was ejected from the star in a previous outburst, similar to the current one. The *Hubble* images show an extremely rich array of filaments and other features on small physical scales, suggestive of magnetohydrodynamic forces.

Future work on the *HST* images are expected to yield dust physics (i.e., the angular and color dependence of the scattering function) and a fully three-dimensional map of the dust distribution at high spatial resolution.

Figure 4. Left: *HST* image of V838 Mon on 2005 November 17. The surface brightness is highest along an "equatorial plane" passing through the star, marked with a dashed line to guide the eye. Right: amateur photograph of the planetary nebula M27. Note the striking resemblance of the light echo's structure to that of the planetary nebula.

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